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HEAT TRANSFER FROM AN INCANDESCENT WIRE IN SATURATED LIQUID NITROGEN FROM ATMOSPHERIC TO THE CRITICAL PRESSURE

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SUMMARY

Film boiling off horizontal platinum wires in saturated liquid nitrogen at 1 g has been examined at pressures up to 33 atmospheres and wire temperatures approaching the melting temperature of platinum. The experimental data are compared to existing correlations. It is shown that present film boiling correlations do not predict the correct trends for increasing wall to bulk temperatures.

INTRODUCTION

Although the field of film boiling has been examined extensively both analytically and experimentally, both data and analyses are lacking at very high wall to bulk temperatures and heat fluxes. The present paper presents experimental film boiling data from a wire to liquid nitrogen from atmospheric to the critical pressure with high heat fluxes where the wire becomes incandescent. A comparison with existing correlations is also made.

This data range is important since modern technology is moving in the direction of higher temperatures and heat fluxes. In addition, heat transfer from incandescent wires in cryogenic fluids can be important in safety considerations for space vehicles, as evidenced by the results of the Apollo 13 accident investigation. Also, high temperature film boiling can occur during reflooding of a nuclear core following a loss of coolant accident.

References 1 through 6 have examined various aspects of steady state film boiling from horizontal cylinders. Because of paper length limitations, no detailed discussion of this literature will be presented here.

Most pertinent to the present work are references 3, 4, and 5 in which results of studies of film boiling heat transfer to liquid nitrogen are presented. In the reported works, a correlating equation for liquid nitrogen was presented in the form

$$\mathrm{Nu} = \text{constant} \left[\mathrm{GrPrH}\right]^{1/4} \left[1 + \frac{9}{\sqrt{6}} \frac{L}{D} + \frac{8}{3\sqrt{6}} \left(\frac{L}{D}\right)^3\right]^{1/4} \tag{1}$$

In reference 5, the constant in equation (1) was found to be 0.373, and the properties were evaluated at the film temperature T_f.

Equation (1) depends on the surface tension σ which is contained in the characteristic length L (see nomenclature). In reference 3, the characteristic length L accounted adequately for the effects of wire size on heat transfer at pressures far from the critical pressure. On the other hand, near the critical pressure, Abadzic and Goldstein (2) did not observe experimentally the expected increase in Nusselt number that equation (1) predicts. They suspected that the functional dependency of Nusselt number on L in equation (1) is not valid near the critical point.

The reason for this discrepancy in the data is unknown and, no doubt, more data will be required to resolve this problem. Over a wide pressure range, however, the experiments tabulated in reference 6 seem to support a correlating equation which depends on the characteristic length L.

In detail, the present paper will report experimental saturated film boiling heat transfer data at 1 g for the following range of conditions:

$$0.03 \leq P/P_c \leq 0.98$$

$$2.5 \leq T_w/T_S \leq 20$$

$$4.0 \leq T_w/T_{crit} \leq 13.3$$

$$q \leq 100 \text{ watt/cm}^2$$

Next, attention is paid to the effect of the increased wall to bulk temperature ratios on the correlating trends given in equation (1).

EXPERIMENTAL PROCEDURE

Platimum test heater wires 0.0254 cm in diameter were mounted horizontally under spring tension in a double walled vessel containing saturated liquid nitrogen under pressure. The pressure level and bulk temperature were measured with the appropriate instrumentation (3). The average wire temperature was determined indirectly by calculating the resistance of the wire from voltage and current measurements. A detailed discussion of the experimental equipment and the accuracy of the measurements can be found in reference 3.

DISCUSSION OF RESULTS

The experimental heat transfer coefficients $(h = q/\Delta T)$ are plotted in figure 1 as a function of the critical pressure ratio, P/P_c. The parametric curves are for various levels of the heat flux q. The data shown in figure 1 were taken on a single day with no intermediate adjustments on the equipment. In this manner the trends due to increased heat flux and pressure are more clearly shown by eliminating the day to day scatter that occurs with a new wire. The smaller inserted figure indicates the scatter which occurred for data taken on various wires at atmospheric conditions over a 6-month period of time.

For a given heat flux, the data displayed in figure 1 indicate that the overall heat transfer coefficient reaches a maximum value for a critical pressure between a P/P_c of 0.6 to 0.7. The relative position of the peak with respect to P/P_c seems insensitive to the level of heat flux. These results are consistant with the earlier results of Simoneau and Baumeister (3). The higher heating rates did not produce any new anomalies or trends. However, a problem did arise at these higher heating rates in correlating the data.

Figure 2 depicts the experimental and theoretical trends of the calculated heat transfer coefficient for increasing wall to bulk (saturation) temperature ratios. The calculated curves are constructed from the relationship

$$h = h_f + \frac{7}{8} h_r \tag{2}$$

with

$$h_r = \frac{\epsilon_w \sigma \left(T_w^4 - T_s^4\right)}{\left(T_w - T_s\right)} \tag{3}$$

The factor 7/8 was suggested by Bromley in an earlier work. The values of emissivity as a function of temperature were taken from the curves in reference 7. The radiation is generally small (less than 10 percent at highest wire temperature) compared to the film boiling component.

For relatively low wall to bulk temperature ratios, experiment seems to approach theory at the lower pressures. However, at high wall to bulk temperatures a large disparity between experiment and theory is seen.

Speculation as to why such a disparity exists will not be considered herein.

As seen in figure 2, between a pressure ratio of 0.94 and 0.98, the theory shifts from an underprediction to a large overprediction. The behavior between prediction and experimental data within this pressure span and the critical pressure is not understood at this time and warrants further investigation. This is a regime where the correlation is extremely sensitive to the fluid properties (including transport properties). This may substantiate Abadzic and Goldstein's (2) comments that equation (1) is too sensitive to the characteristic length L near the critical pressure.

Nevertheless, equation (1) does seem to give a reasonable correlation of the data (25%) over a wide range of pressures and temperatures.

NOMENCLATURE

C_p	vapor specific heat at constant vapor pressure
D	diameter of wire
Gr	defined by $\rho_V(\rho_L - \rho_V)\, gL^3/\mu^2$ evaluated at film temperature
g	coefficient of gravity
g_c	conversion factor
H	defined by $\lambda^*/C_p\, \Delta T$
h_f	film boiling heat transfer coefficient
h	total heat transfer coefficient
h_r	radiative heat transfer coefficient
k	thermal conductivity of vapor
L	characteristic length defined as $\sqrt{\sigma g_c/g(\rho_L - \rho_V)}$
Nu	film boiling Nusselt Number $h_f L/k$
P	system pressure

P_c	critical pressure
Pr	Prandtl number $C_p\,\mu/k$ evaluated at film temperature
q	heat flux
ΔT	temperature difference $(T_W - T_S)$
T_{crit}	critical temperature (126 K)
T_f	film temperature $(T_W + T_S)/2$
T_S	saturation temperature of liquid
T_W	wire temperature
ϵ_W	emissivity of wire
λ	latent heat of vaporization
λ^*	modified latent heat of vaporization $\lambda^* = \lambda[1 + 0.34\,C_p\,\Delta T/\lambda]^2$ given in ref. 6
μ	viscosity of vapor
ρ_L	liquid density
ρ_V	vapor density
σ	surface tension
$\bar{\sigma}$	Stefan-Boltzmann constant

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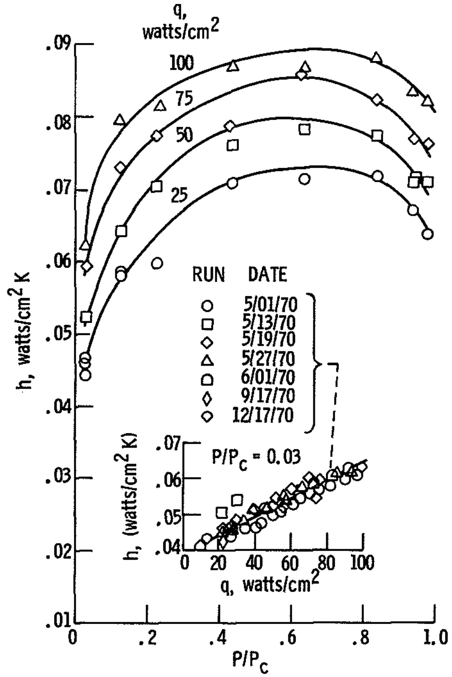

Figure 1. - Measured values of the total boiling heat transfer coefficient as a function of the pressure ratio and heat flux (P_c = 33.5 atm).

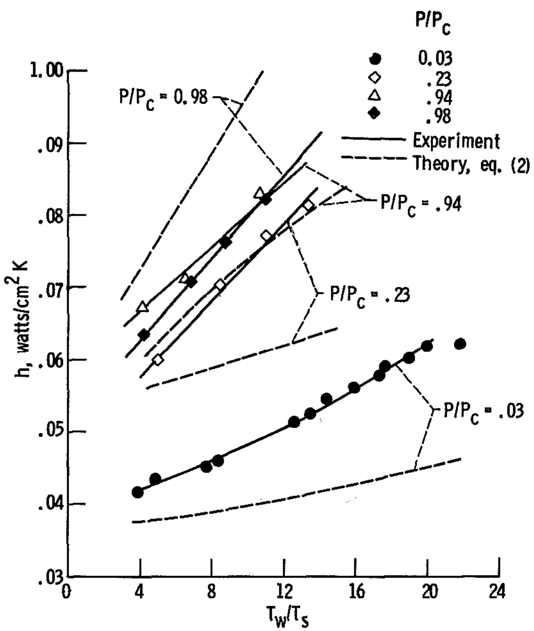

Figure 2. - Comparison of experimental and theoretical values of the heat transfer coefficient as a function of the wall to bulk temperature ratio.